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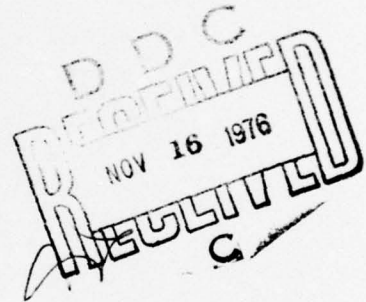
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SPECIAL INJECTIONS: REPAIR, CONSOLIDATION, WATERTIGHTNESS

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C. Caron



CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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ANNALS OF THE TECHNICAL INSTITUTE OF BUILDING AND
PUBLIC WORKS

22nd Year, September 1969, No. 261

Series: MATERIALS (39)

CENTER FOR ADVANCED STUDIES -- Meeting of 10 December
1968 under the Chairmanship of Mr. Armand Mayer, Engi-
neer General of Mines (Ret.), Chairman of the French
Committee for the Mechanics of Soils

SPECIAL INJECTIONS: REPAIR,
CONSOLIDATION, WATERTIGHTNESS

Engineer C. Caron, Ph.D.,
Director of the Laboratory
of the Société Solétanche

TECHNICAL INSTITUTE OF BUILDING AND PUBLIC WORKS

Special injections with grouts having an organic resin base have been developing during the past few years and can be divided, for the sake of simplicity, into two main categories:

a. Precondensed Resins Without Solvent

These are thermohardenable resins that polymerize cold under the influence of a hardener (polyepoxy, polyurethane) or of a catalyzer (polyester, polysulfide) or even sometimes of the simple air moisture water serving in this case as a catalyzer (silicon and certain polyurethanes). These resins, once catalyzed, acquire great strength sometimes associated with a marked elasticity. They serve mainly, within the framework of injection, for the treatment of concretes which have cracked or which are of poor quality.

b. Monomers Soluble in Water

Certain monomers of the acrylamide, phenoplast and aminoplast type have the property of being able to be dissolved in water in any proportion and of polymerizing cold without separating from the mixture water. The mechanical characteristics of these aqueous solutions after polymerization are obviously much lower than those of resins without solvent, and this class of products is therefore limited especially to use for the purposes of water-tightness or to consolidate fine cohesionless soils. They have, in fact, the interesting property of being much more fluid than all traditional products basically made of cement, silicate, lignosulfite, etc.).

*Numbers in the right margin indicate pagination in the original text.

I have today the very agreeable task of presenting to you our lecturer, Mr. Caron, Laboratory Chief and Operations Chief of the Société Solétanche. He is a graduate of the National Advanced School of Chemistry of Paris. He received his doctor's degree in engineering after presenting a thesis on silica gels, and he is the author of a number of works which most of you certainly know.

I do not believe I need to introduce him at any length because he has already given three lectures in this hall, one in 1964 on the setting of concretes and setting delayers, another in 1966 on silica gels as well as a third one in 1967 on concrete adhesives.

His subject today is: Special injections: repair, consolidation and watertightness. These are subjects which are currently important and no other proof of their interest is necessary than the number of those of you who came to hear him.

There are probably two reasons why I was requested to chair this conference. One is my seniority. I have now spent more than 30 years with the firm before it was even called Solétanche. We had the opportunity of working at the Sautet Dam and, above all, we worked at Genissial where we for the first time made injections into the permeable alluvions at the same time using chemical products. The other reason is that there will be a discussion today of those special works performed at the Koyna Dam in India. These are works which I had the opportunity of proposing during a mission performed for UNESCO as a consequence of the unsettling of this dam by an earthquake.

I shall leave the whole technical report of the works of course to Mr. Caron. I should merely like to say a few words to you concerning the conditions in which I was led, in the same way as Mr. Bellier, with whom I had been associated at the Koyna Mission, to propose awarding to Mr. Caron the supervision of very difficult and very delicate works which had to be accomplished at the dam in order to restore its solidity before the monsoon period.

The region where the Koyna Dam was constructed is found south of Bombay at the edge of the Dekkan Plateau. This plateau is entirely covered over by a basaltic flow superimposed on old terrains going from the albian to the jurassic area. This zone was, until the Koyna accident, considered as completely aseismic, contrary to a great number of regions in the north of India where seismic activity is quite great.

Following the earthquake, investigations revealed that 23 earthquakes had been experienced during the last 400 years in this region with one of them being in 1618 in Bombay itself. However, although 13 of them were felt between 1751 and 1764, no earthquakes had occurred since that period to such an extent that any memory of them had been completely erased and the Koyna Dam had been designed with the hypothesis of a horizontal acceleration of 0.05 g corresponding to a practically zero seismicity.

As soon as the reservoir was filled in 1962, small tremors were felt in the dam area. This was, furthermore, a rather frequent observation corresponding to fracturing of the rock in depth under the effect of the load on the reservoir when the latter has a sufficient surface and depth.

Owing to this fact, as early as 1964, seismographs were installed in the vicinity of the dam.

From 10 September 1964 to 12 September 1967, 154 tremors were noted, having an amplitude included between 2 and 3 on the Richter scale. The epicenters were located directly below the reservoir and between 3 and 5 km in depth.

On 13 September, two tremors were observed with a magnitude clearly greater than the first ones and having an amplitude on the order of 5 to 5.5. A number of constructions were slightly damaged, but the dam itself was not affected.

The seismic activity continued during the following two months. It was on a reduced scale. However, on 10 December, a shock with an amplitude on the order of 7 occurred which was noted by the specialized sites of the entire world. This shock produced serious damage. The village built on the side of the dam was completely crushed. The cables which supplied the region from the subterranean plant were broken. The whole city of Bombay was plunged into darkness. Another more annoying consequence for the observers was the fact that all of the recording equipments located in the dam were deprived of electricity with the exception of one of them using battery current located in a gallery at midheight which noted a horizontal acceleration of 0.8 g. This is clearly quite far from the 0.05 g taken into account in the calculation.

In spite of this, the dam did not show too serious disturbances and could be kept in operation. Nevertheless, along the line of slope change of the downstream face, at about 40 m from the crest, a horizontal fissure developed which during the shocks allowed water to filtrate at two points, thus being the clue to a complete rupture of two units.

As a result of a first survey made by Japanese and Indian geologists and seismologists followed by the second one which I have just mentioned in which Mr. Bellier and myself took part (Mr. Guyon having likewise been there in the interim), it was decided that the repair of the dam would involve two phases:

First of all, give the dam back its qualities of stability and monolithism as quickly as possible since it was not possible to avoid filling up of the basin during the monsoon season and a new tremor could occur at that time.

It was then necessary, after the monsoon season, to reinforce the dam in order to ensure its stability at least for a tremor similar to the one which had occurred and which corresponded to 13 times that which had been taken into account in the computations.

The first objective was, therefore, to attach the upper part of the dam to its base, and this is what will be discussed by Mr. Caron. I do not wish to further delay his opportunity to speak, and I now give him the floor.

In a recent meeting of a research group of laboratory chiefs of the Department of Civil Engineering, one of the lecturers very appropriately recalled the words of Matthew:

"Every one then who hears these words of mine and does them will be like a wise man who built his house upon the rock. The rain fell, the floods came, the winds blew and beat upon that house, but it did not fall because it had been founded on the rock."

In my contribution, I took the sentences and adapted them in the following commentary: "effectively over the centuries, only the wise man who built on the rock was sure to preserve his house but, for some time now, he can also build his house on any ground whatsoever. All he needs to do is to call upon an injector."

In reality, all defective terrains, whether they are fissured or incoherent, can be consolidated by injections. This has been possible for a number of years for relatively permeable terrains. However, it has only been quite recently that it has been known how to deal with fine powdery soils. These consolidations have been possible by the systematic use of organic resins.

No industrial development, aside from perhaps that of electronics, has been as swift as that of plastic substances. It is possible to find ancestors in past centuries to the automobile or the aircraft. There is, however, nothing like this at all in the field of plastic substances.

The works in chemistry at the beginning of the century, still of use today on many points, show how applications of phenol formaldehyde assist manufacture of dyes and disinfectants. Insofar as ethylene and propylene are concerned, the applications mentioned are still more restricted and, nevertheless, 50 years later, these basic products will be used in millions of tons in the manufacture of plastic substances. Such a gradual development has transformed everyday life and, quite naturally, it has affected the industries involved in construction and civil engineering.

The plastic substances are, for the most part, delivered in a state of manufactured objects which have replaced in a great many applications wood, glass, metals, textiles and natural rubbers. This arises particularly from the fact that the plastic substances are much more practical in industry in application than the abovementioned materials and that they quite often have more advantageous physical properties.

In much rarer cases, the plastic substances are supplied in a liquid state and it is the user himself who ensures their transformation into solids. The role of the user is, in this case, much more difficult since he must do this at the work site under poorly specified conditions that which is generally performed in the factory under perfectly controlled conditions. This liquid plastic substance can be without a solvent or, on the contrary, dissolved in a solvent, one especially advantageous case

being that in which the solvent is water. The utilizations and final products will be quite different in both cases, and it is this classification which we shall use for this report.

PART ONE

UTILIZATION OF LIQUID PLASTIC SUBSTANCES WITHOUT SOLVENT

We understand by this expression those precondensed resins which generally appear in the form of a more or less viscous oil. They are beginning to become quite well known in our profession for their utilization as an adhesive for concrete, metals, etc... Thus, the last International RILEM* Congress brought together last year in Paris specialists in the question and enabled it to be seen that these products were now studied and used throughout the world. Chemically, these prepolymers belong to various classes: polyepoxies, polyesters, polyurethanes, polysulfides, silicones, etc...

The polymerization transforming this prepolymer into a solid takes effect by catalysis (for example, with the polyesters), by polyaddition (for example, with the polyepoxies), by the ordinary humidity in the air (for example, a number of polyurethanes and polysulfides). There already have been found, therefore, at the minimum, five classes of products, three types of polymerization and, in each one of these classes, several hundred possible variants. This clearly allows solving the most varied problems, but there are still only a few persons who understand how to most efficiently utilize the astonishing properties of these various polymers.

One especially spectacular application is that of the repair of works of art, this repair being accomplished by the injection of prepolymers into cracks in the concrete or other defective areas. I have had the opportunity of discussing with you this type of work last year in a preceding lecture and it was I who worked out the operation needed to save the Temples of Abu-Simbel in Upper Egypt.**

I shall talk to you this year concerning a closer application of conventional civil engineering. This involves the Koyna Dam in India. /1311

The Koyna Dam was damaged on 11 December 1967 by an unusually violent earthquake. I shall borrow some information on this earthquake from the report of the Committee of Experts of UNESCO which committee was under the direction of Professor Okamoto of the University of Tokyo:

Intensity 6.3 to 7.5 on the Richter scale,

* Réunion internationale des laboratoires d'essais et de recherches sur les matériaux et constructions, International Union of Testing and Research Laboratories for Materials and Structures.

**C. Caron: Application of Synthetic Resins in Civil Engineering. Annales d l'Institut Technique du Bâtiment et des Travaux Publics. Series Materials No. 33. July-August 1967.

Epicenter 3 km to the south of the Koyna Dam,
Radius of the detection area: 600 km.

The experts noted that this was the first time in the world that an earthquake of such violence had its epicenter so close to a dam. During the Kitamino earthquake in 1961, with a 7 intensity, the different dams of the region were respectively 15, 30, 40 or 45 km from the epicenter which was consequently much less serious than at Koyna.

A second mission from UNESCO, including Professor Armand Mayer as well as Mr. Bellier, had the goal of determining methods of repair. In order of execution of works, three methods were used:

Sealing of the cracks by injection of resin,
Emplacement of cables in the dam,
Widening of the base of the dam.

The UNESCO was eager to give me a research mission involving the application of the first repair method.

Figure 1 shows a general view of the dam. It is a gravity dam made of cyclopean concrete of an excellent quality. Furthermore, it should be recognized that it is owing to the special care given the concrete itself and the design of the work that the latter was able to resist the earthquake without undergoing more considerable damages. It includes 31 monoliths and only the 14 monoliths in the center were damaged (Figure 2). Out of 12 of these, the crack, although simultaneously apparent on the upstream face as well as the downstream face, does not pass through the dam and, in most cases, is relatively short. On the other hand, with the two monoliths 18 and 26, the crack passes more or less through the dam. This suggests two different modes of treatment:

Short Cracks Not Passing Through the Dam

They affect most of the monoliths of the center. On an order of magnitude, this represents 100 meters visible on the facing upstream and 150 meters on the facing downstream. These cracks were treated with epoxies from a network of short drillholes, the latter being spaced approximately 1 meter apart. Since this involves relatively short cracks and the distance between drillholes is quite small, the quantity of resin injected per drillhole was always less than 1 meter. For this reason, it was possible to use a light equipment (a sort of large syringe) as well as a relatively viscous injection product with a short setting time. The epoxies manufactured in India turned out to be quite suitable for this injection.

Cracks Passing Through the Dam

This is the case of the two monoliths 18 and 26. After having examined all possibilities for treatment, it appeared to us, taking into account the short time available (it was absolutely necessary for these works to be completed before the monsoon season), that the best method consisted

in injecting with a more rational equipment a very fluid resin having a very long setting time such that it would be possible to treat this zone with a minimum of drillholes.

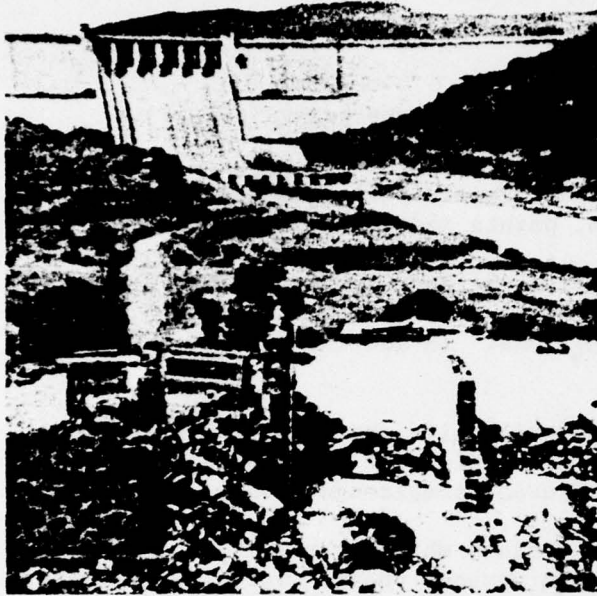


Figure 1. General view of the Koyna Dam.

The injection equipment was made up by 50 liter Johny devices allowing a swift injection using compressed air pressure controllable between 1 and 7 bars. The compressed air was filtered and dehydrated on a preliminary basis (Figure 3). The injection resin was a fluidified polyester whose catalytic content had been selected as low as possible.

/1312

Two international companies assisted the Indian Administration in these special works which, in spite of a number of supply

difficulties, were able to be completed within very short times on the order of two months. The checks and corings carried out both in the area injected with polyepoxy as well as in the area injected with polyester justified the selection of methods and products used.

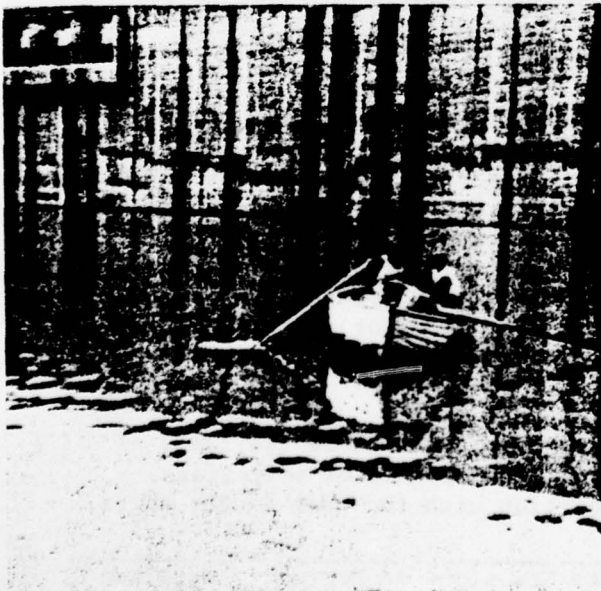


Figure 2. View of the cracked central segments.

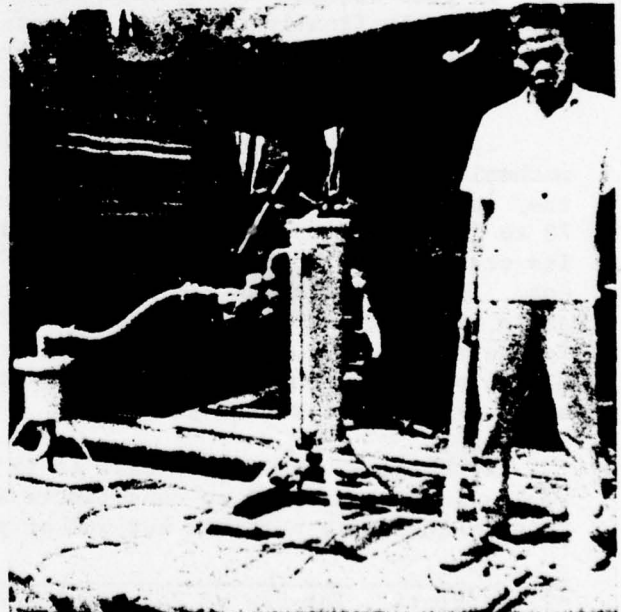


Figure 3. Injection equipment.

We find here one of the "golden rules" of injectors. It is necessary to always adapt the viscosity of the injection grout to the size of the crack or the cavities to be filled. We shall find this rule again in Part Two of the text devoted to resins for treating powdery soils.

PART TWO

UTILIZATIONS OF RESINS IN SOLVENT PHASE

The plastic substances in solvent organic phase are quite widespread. Included in these are, among others, paints and varnishes.

The plastic substances in emulsion whether organic or more frequently aqueous are also quite well known. Quite recently, Mr. Mattioti* talked to us here concerning polyvinyl emulsions. In addition, there are dozens of others with quite varied uses.

Some polymers in aqueous or hydroalcoholic phase are likewise quite frequently used. Let us mention, for example, the wood adhesives with precondensed phenol-formaldehyde for urea-formaldehyde base.

Nevertheless, there is still one class which is rarely studied, and this is the one concerning monomers in aqueous phase. Very few monomers dissolved in water can be polymerized cold at the same time keeping their water which then forms an integral part of the polymer. In some cases which are then still more interesting, the water-monomer-catalyst mixture has the property not only of being as fluid as water but still undergoing no increase in viscosity until the setting en masse.

It goes without saying that such a property arouses the interest of injectors who finally found the "miracle" product capable of treating all permeable terrains since it follows exactly the same path as water and with the same ease since it has its fluidity.

It goes without saying that these aqueous resins cannot have the same mechanical performances as those which we discussed in Part One. Indeed, they polymerize with water which they use as support. The approximately 70 to 95% of water associated with resin in this way obligatorily affect its stability. The fields of applications are therefore totally different. In the first case, it was a matter of sealing cracks in such a way as to give back to the work its strength and initial monolithism whereas, in the second case, it will be a matter of leakproofing or consolidating hardly permeable uninjectable powdery terrains with customary grouts such as clay-cement or silica gels.

We believe, therefore, that it is illogical to use these two types of resins and rather seek to consolidate a sand with epoxies or polyesters. This is certainly possible but out of proportion with the goal sought after.

*P. Mattioti: The Use of Polyvinyl Acetate Emulsions in Mortars. Annales I.T.B.T.P., No. 257, May 1969. Series: M/37.

We have discussed this matter a number of times with the manufacturers, prime contractors and councils. Frankly, it should be admitted that the use of precondensed polyester, epoxy, nonfoaming polyurethane resins is only justified quite rarely in terrain injections since the working load required is quite low.

Quite exceptional conditions are required to justify nonaqueous resins for injection in terrains. I have only seen two cases in 10 years. I spoke to you last year about the one involving consolidation of the sandstones of Abu-Simbel perpendicular to the anchoring bars. Nevertheless, I should above all like to give to my colleague and friend, F. Rosset, the right of authorship for an original although older production towards 1960, that is to say at a time when utilization of resins for injection was practically unknown. /1313

This involved, for the foundation of a pylon, giving stakes with a small diameter (\emptyset 10 cm) the same supporting force as that of standard piles. At the base of the pile which rested on sandy aquiferous terrain, a resin bulb was sealed by injection. This operation allowed quadrupling the supporting force of the piles. The main difficulty was adjusting to less than 0.5% the density of the resin such that the 50 liters injected grows quite slightly before polymerization in order to perfectly cap the base of the pile and to ensure its monolithism with the injected bulb.

Nevertheless, aside from these several exceptional consolidations connected with tierods, anchoring bars or piles, the majority of treatments of fine terrains will be done with aqueous resins.

In the present state of art, only three types of monomers are recognized which correspond to the definition given above or: cold polymerization with water of the mixture, initial velocity identical to that of water, nondevelopment of viscosity up until polymerization en masse. These three resins are:

The acrylamides whose first manufactures and applications were developed by the Cyanamid Company under the name of AM 9, mainly in the United States. In addition to their rather high price, the main objection that could be made to them is that they cannot lead to high stabilities no matter what the concentration of monomer. Their field of application will therefore be watertightness or, at worst, a very moderate consolidation.

On the contrary, the urea-formaldehyde and the resorcine-formaldehyde, depending on their dilution, can resolve just as well problems of watertightness as those of consolidation (up to 100 bars with injected terrain). The resorcine-formaldehyde resins polymerize in an acid or basic environment whereas the urea-formaldehyde resins can only polymerize in an acid environment which makes them difficult to use in a limey terrain. For this reason, we have produced about 50 various sites using resorcine-formaldehyde resins and we have only, up until the present time, used urea-formaldehyde resins one single time.

These aqueous resins are purely Newtonian grouts without granules. From this dual viewpoint, they are therefore differentiated from cement-based grouts. On the other hand, they correspond to the same definition as silica gels or lignochrome. Their difference with these latter substances rests exclusively in the value of the viscosity and the gradual development of the latter during setting.

The solutions of alkaline silicate or lignosulfite, even when they are quite dilute, always have a viscosity greater than that of water since it concerns colloidal solutions. The initial viscosity for dilute solutions (which lead to soft gels) ranges from 5 to 10 centipoises and for concentrated solutions (which lead to hard gels) ranging from 15 to 50 centipoises. In addition, this viscosity increases starting with introduction of the gelifying reactant such that it can be considered that these values are doubled at the end of about 20 minutes.

On the other hand, the noncolloidal solutions of the three abovementioned monomers have a viscosity almost equivalent to that of water (hardly more than one centipoise at 20° C) and which is not modified until the setting en masse (Figure 4).

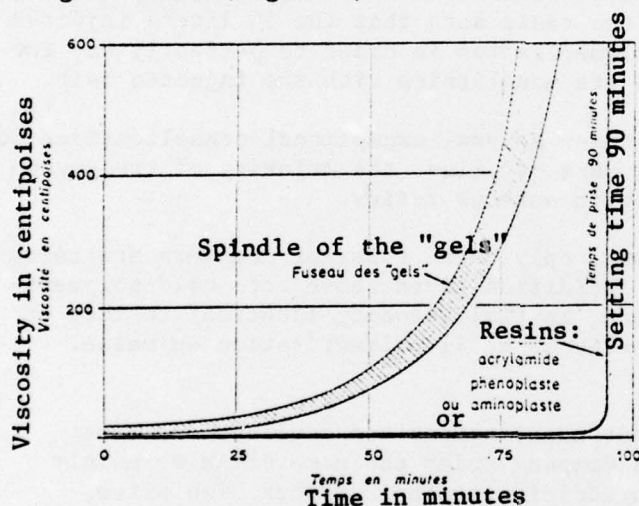


Figure 4. Evolution in time of viscosity of gels and aqueous resins.

All things being equal, furthermore (same terrain and same injection pressure), an aqueous resin will therefore be able to be injected 10 to 100 times more quickly than a gel (direct consequence of Darcy's Law).

Theoretically, it would be possible to inject gels into extremely fine terrains, for example silts with a permeability of 10^{-6} m/s. This, however, would imply such low injection rates that the operation could hardly be profitable. Also, in the present state of art, the injection of gels is generally limited to terrains whose permeability is greater than 10^{-5} m/s. Below this point, resins are used.

It could also be planned to assist penetration of an overviscous product into the pores of a terrain by increasing the injection pressure. However, in this field, a limitation quickly appears in the terrains close to the surface because heaving and puncturing would necessarily be caused.

Therefore, aqueous resins are quite useful mainly for injection of fine terrains with shallow depth.

What we understand by the term aqueous resin should likewise be well specified. For us, these grouts are purely Newtonian solutions of monomers having a viscosity identical to that of water and not changing in viscosity before setting. It is therefore a rheological definition which we give to the term of aqueous resin and not a chemical definition. If a saline solution could harden by itself after injection, it would correspond to this definition and, on the other hand, if a resin in solution in water endows the latter with a nonnegligible viscosity and that, in addition, this viscosity increases as soon as prepared, we shall consider that we are no longer concerned with an "aqueous resin" and that this product now enters the class of "gels".

This is good sense but has unfortunately not been understood by everyone.

For five or six years, with more or less good faith, a certain number of manufacturers have been speaking highly of resins for injection of fine terrains to the specialized enterprises or the prime contractors. In the chemical field, the term is exact although most of the products which we analyzed were not monomers but prepolymers and had, owing to this fact, a considerable initial viscosity which continued to increase as soon as the catalyst was introduced. The curves which we have obtained enter perfectly into the range of "gels" of Figure 4.

/1314

The user should therefore distrust the terminology and measure with the viscometer the product suggested to him since even though these false "aqueous resins" allow by injection to give the terrain the characteristics required, it is also certain that the same result could have been obtained more economically with a simple "gel".

Just as in the case of silica gels, the strength of the final product will be proportional to the concentration of the monomer in the grout according to a relation which is practically linear. For example, with the resorcine-formaldelyde, a resin content of 5% will be generally sufficient for a watertightness whereas it will be from 10 to 25% for a consolidation. Since this involves rather expensive products, there is an advantage of well specifying the strength since the latter is directly related to the concentration and consequently to the price.

We have likewise discovered that the strength of the terrain treated was related to its particle-size analysis according to the same empirical formula already referred to for the gels:

$$R_t = R_p (1 + k \sqrt{S})$$

R_t being the strength of the terrain treated,

R_p being the strength of the pure aqueous resin,

S being the specific surface of the terrain.

The proportionality factor k is a function of the nature of the resin. It is generally less strong than in the case of gels.

The chemical nature of the terrain also has its effect. This is clear in the case of a polymerization reaction in acid phase (urea-formaldehyde). This is less so in the case of reactions in basic phase. Nevertheless, we have found a number of differences with the resorcin-formaldehydes.

A number of work sites have been produced using these aqueous resins. They can be related to three groups:

Watertight treatment of the concrete in its mass: In difficult cases, this method has proven more reliable than those of surface coatings. It is obviously more burdensome.

Treatment of fissured terrain: This is a relatively rare case since, in most cases, it is possible by using a strong pressure to open up the cracks and allow in this way injection of dilute cement.

Watertight treatment or consolidation of fine sands, silts, etc...: This has been up until now the most frequent application case. In order to show its limits, we have provided in Figure 5 a number of particle-size curves of terrains treated with aqueous resins.

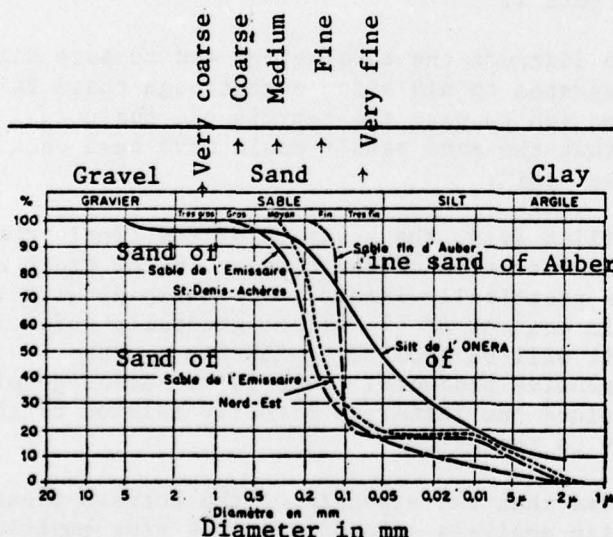


Figure 5. Particle-size analyses.

The most spectacular application which we have had with the resorcin-formaldehydes occurred last year within the scope of the construction of the Metro Express Subway for the future Auber Station. This concerns the largest station of the Metro Express since six lines joined there.

The station, entirely constructed under the phreatic nappe (2 kg/cm² of pressure for the floor), will be 239 m long, 39 m wide and 19 m high.

It is located on Metro Line Number 3 and under the most important sewer of the City of Paris. Finally, large buildings and even part of the opera are directly at right angles to this station. All of these combined conditions made opening of a station such as this especially difficult since it was desired to avoid creating surface disturbances. Figure 6 provides an overall view of the future station whereas Figure 7 shows a cross section of the different terrains.



Figure 6.
Cross section through
the Auber Station of
the Metro Express sub-
way line.

It can be seen that in a large part of the station and in the totality of the related work, the excavation will cut through a zone of extremely fine Beauchamp sand whose average permeability is 10^{-6} m/s. It goes without saying that a terrain as little permeable as this is difficult to inject without punctures and heavings with all the traditional products including silica gels.

/1315

Gravelly and ordinary marls have therefore been injected into the clay-cement according to traditional methods. Sandy gravel alluvions were injected with hard acetate gel. These are methods which I discussed with you here in 1965.* There is also the method of aqueous resins for treating the sands of Beauchamp.

For the site and the associated works, injections of $25,000 \text{ m}^3$ of clay-cement, 6500 m^3 of hard gel and 5000 m^3 of resin were made in 135,000 m of drilling.

The treated terrain had, in all cases and notwithstanding its degree of fineness, a minimum strength of 20 bars which allowed excavation to be made with all safety and without any considerable disturbance on the surface.

*C. Caron: Consolidation of Sands by Injections of Silica Gels. Annales de l'Institut Technique du Bâtiment et Travaux Publics. Series: Essais et Mesure, No. 85. September 1965.

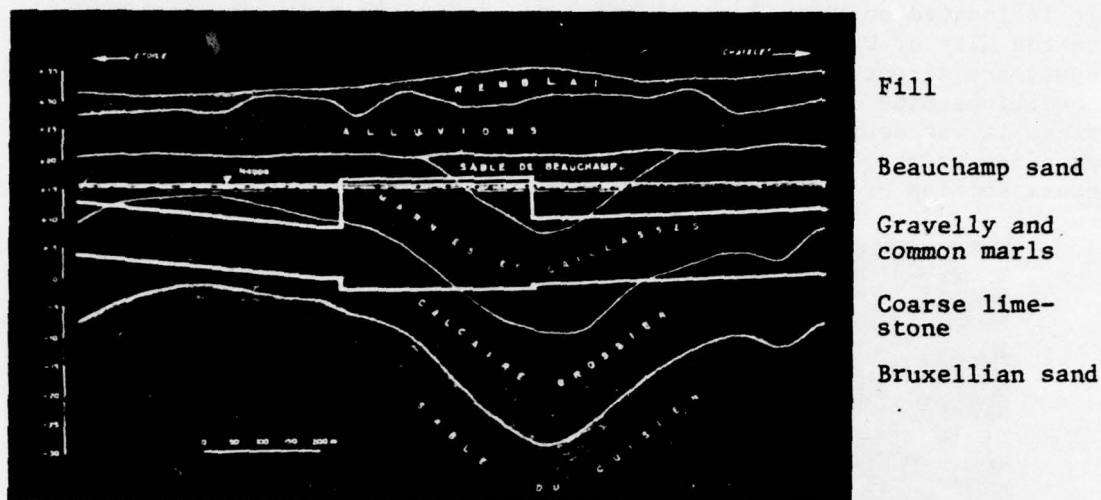


Figure 7. Aubert Station of the Metro Express. Geological cross section of terrains encountered.

The wise selection of injection products becoming more and more fluid to the extent that the terrain became finer in composition, allowed limiting heaving to quite acceptable values.

There still could be much said concerning these resins. They can be used as an adhesive for the cement or for consolidation of soils which are poorly permeable. We could discuss their limited performance in the various fields of application, their behavior in an aggressive environment, their lasting quality, their possible toxicity, etc... However, I prefer to leave more time for the discussion which will follow.

DISCUSSION

Mr. Chairman

In your name and mine, I should like to thank Mr. Caron for his excellent report. I see that, in accordance with the agenda, he is ready for the discussion. In this case, we shall wait as he has said for questions to be put to him which he will certainly be quite ready to answer.

Mr. Fénélon

Resins are as a general rule thermohardenable. Putting pressure aside, what is the limiting temperature allowing their polymerization?

What actually replaces the high temperature for polymerization?

Mr. Caron

This is a very reasonable question. We will have to discriminate again between the resins which I have discussed in Part One (the adhesive resins) and in Part Two (the aqueous resins). Both of these resin types are thermohardenable, i.e., they harden generally with increase in temperature. The astuteness found in the Department of Civil Engineering was in being able to use them without an increase in temperature. Nevertheless, what is the minimum temperature at which they will react?

First of all, let us consider adhesive resins. Within the scope of epoxies, up until a few years ago, the use below 15° C was not advised. Despite this, progress has been made. There are now a number of epoxies which react down to 0° C.

In the case of polyesters, a temperature of 0° C has no inhibiting effect at all, and it is even possible, when necessary, when the terrain is dry, to use them below 0° C.

I say when the terrain is dry because when it is wet the water would be transformed into ice, and it would not be possible to make the injection. This is not a question of nonaffinity of the resin with water.

In the case of aqueous resins, it is possible to consider a temperature of 0° C. It is enough that the mixture is not frozen. Our Swiss colleagues have used them at Mattmark where 0° C often occurs and occasionally a little below. Clearly, the setting time is always extremely elongated at low temperature. This is in accordance with the law of Van T'Hoff-Arrhenius, i.e., when the temperature is 10° C lower, the setting time is three times longer. I believe that this is practically all there is to say on the question of temperatures.

Mr. Fénélon

And the cost prices?

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Mr. Caron

In the case of precondensed resins which are intended for retiring concretes -- because I place myself exclusively within the scope of injection on this occasion -- the cost price of resin has practically no effect on the repair cost since, except for the example of Tolla where 20 or 30 t of resin were used, in general the quantities do not exceed 20 to 30 l. Consequently, it is the cost of labor and not that of the resin which is a factor in the total cost.

In the case of aqueous resins which are used in a quantity much greater than that of nonaqueous resins, the cost of the resin is clearly a handicap to some extent. This is the reason why we have very intensely developed the formaldehyde-resorcines. If the work on the Metro, for example, had been accomplished using acrylamides, it would have been much more expensive and resistances to compression amounting to 20 bars would not have been obtained.

Mr. Furnal

Is there a work site method which would allow seeing if an injection had actually succeeded in its totality? I am speaking of rather fine terrains. Is there a detection method with partial or total fillings?

Mr. Caron

Yes. When a mass treatment is carried out, there are generally operations in two phases. There is a first gridding series used with injection. The second gridding series, before being used for injection, is used for making water tests. Consequently, it is realized when the permeability of the terrain has been decreased. If it has not been sufficiently decreased, the second gridding will be used in its totality. When these two gridings are completed, checks are again made and if the permeability is still insufficient, the injection is continued.

Therefore, injections are carried out up until the instant at which the terrain is perfectly full. This does not provide an indication of the strength and merely means that the terrain is perfectly injected. However, as in the laboratory, an accurate determination has been made as to what was the strength of the full terrain, and it is possible to be almost ensured of producing the anticipated strength.

It is likewise possible to make a core sampling.

In any case, I should like to point out that there are methods which provide no information. These are generally the sonic as well as electrical methods. Much more traditional methods should still be used such as water tests, core sampling and placing confidence in laboratory tests.

Mr. Gosset

I am studying the case of a retaining wall 4 to 5 m in height of which one part has crumbled. Poorly constructed, it is 70 to 100 years old and

its mortar has crumbled. In order to allow its repair without risk of causing new collapses, is it not possible to solidify the terrain in order to prevent this from happening?

Mr. Caron

It is possible that this is an injection case, but there are just so many methods of consolidation that I cannot tell you now whether this is a case in which injection is the most desirable method or whether you should call upon tierods, an electrical consolidation, or even merely repairing the underground structure with piles ...

It is clear that much is possible by injection. However, in many cases, much more traditional methods such as piles, trenches, excavations, etc... can very well be used and turn out to be less expensive than the injection method.

The goal of my report has been to show that we now know how to inject all types of soil, but this does not mean that it should be absolutely based on a soil consolidated by injection. Your case is a little too precise.

Mr. Gosset

This involves a fill terrain which does not support a load and that it is only necessary to stabilize.

Mr. Caron

In the case of injection, a gel would be used if the terrain is permeable on an average basis and a clay-cement grout if it is very permeable and a resin if it is very fine.

Mr. Chairman

What is important is knowing what you intend to do.

Mr. Tincelin

Do you know examples or have you had experience in consolidating cracked rocks by resin injection?

Mr. Caron

We have only had two applications of injection of aqueous resins into cracked rocks in 10 years which is indeed extremely few.

This is due to the fact that most of the time, as I have said a little while ago, the cracked rock can be injected at very high pressure by a grout of the dilute cement on the condition that it has a permeability greater than two or three Lugeon units.

One case was studied at Kainji in Nigeria in collaboration with the Balfour-Beatty Office. There was under the dam a fault filled with clay

of decomposition which showed danger of loosening and, on both sides of this fault, amphibolites with microscopic cracks. Consequently, it was necessary in order to prevent loosening of the fault to block the microscopic cracks, and it was clearly only possible to do it by a high-pressure injection which would have led to a loosening condition.

It was therefore necessary to make this injection, not with dilute cement at high pressure but with low pressure resin. About 50 drillholes had already been made with cement injection. With the core sampling, not the slightest trace of cement was found in the cracks because the pressure had to be limited. It is then true that we propose to carry out the injection with resin. Into the same 50 drillholes, a phenolic resin was injected and the result was absolutely excellent.

Consequently, in a number of special cases, it is a very valid method although more burdensome, of course, than that of the dilute cement grout. It is chiefly to be used when it is not possible to increase pressure in terrains with low Lugeon units.

We have had another case in Pakistan. The cement injections had allowed reducing the Lugeon units to two or three and, in this special case, it was particularly desired to reach zero. It was therefore completed by a little resin. This was, however, an extremely rare case. This is not recommended for all cracked rocks.

Mr. Raud

Have you had applications for making watertight sedimentary clay schists with very fine cracks whose permeability can only be 10^{-7} m/s, for example, or even less than this value and in which the conventional grouts are often hardly affected?

I should specify that this question is essentially relative to making watertight and not to consolidation.

Mr. Caron

I shall make the same reply to you as before. In normal times, in these cracked terrains, injections under pressure will open the crack. It will, therefore, be possible to pass in cement and clearly this is the most economical method. If you have cases in which this method is not suitable, it can be guaranteed that you will succeed with resins. There is no problem. Since water passes through, the resin will obligatorily pass through. If only watertightness is desired, the method will be relatively economical since very dilute resins will be used.

Mr. Simonnet

What do we know of the service life as well as development of these products in time using a scale of tens of years at the least?

Mr. Caron

It is quite true that these products have not been used in the civil

engineering departments for a very long time which brings about a condition that we find it difficult to give a 10-year guarantee since we have not known them for 10 years. Of course, there are always people who give a 10-year guarantee for a product which was produced yesterday, and this is not to be taken seriously. Thus, up to the present time, we have not given such a guarantee.

Nevertheless, it should be recognized that these resins have small opportunity of being destroyed once polymerized since they are totally insoluble.

In applications in surgery, there are used, for example, derivatives of polyesters in order to make artificial organs or ligatures. This has been true for at least 25 years and in an environment which can be considered as much more aggressive than water of the terrain. Consequently, this gives us confidence. I believe, furthermore, that the doctors and surgeons have been quite daring since it is quite serious to put in an artificial organ when the risk of dissolving or crumbling at the end of a certain time is not known.

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Our civil engineering applications began 10 years ago and no deterioration has yet been noted.

Mr. Simonnet

Have artificial aging tests been made?

Mr. Caron

I do not see how they can be done. It is obviously possible to increase the gradient allowing in this way a possible dissolution to be studied more rapidly. This is practically the only test that could be made. This is not as easy as with painting where, by placing the specimens under ultraviolet light, the aging time is increased tenfold.

Mr. de Schnakenbourg

Experiences shows that, in order to closely bind an epoxy resin coating to a concrete, it is first of all necessary to impregnate the latter with a much more fluid resin. Under these conditions, is it necessary, for the consolidation of a dam, to inject both types of resin into the cracks: one quite fluid in order to feed the pores of the concrete and the other, thicker, which would actually produce the watertightness?

As a corollary, since the carriers are generally prepared before treatment, what occurs, in the field of the bonding, when these cracks are more or less contaminated with mud or excrescences of limestone?

Furthermore, although it is well known that certain epoxy resins adhere well to concrete in a moist environment, it is suggested that the polyesters adhere quite imperfectly to it. Being given that the coefficients of thermal expansion of the concrete and polyester are quite different, don't you believe that, when the repaired work is placed in motion with extreme

climatic conditions (strong insolation or intense freeze) under the effect of fillings and emptyings of the dam, for example, there is in the long run a rupture of adherence between the product injected and the concrete and especially when the injected concrete was moist?

Mr. Caron

With respect to the first question, you have stated quite correctly that in order to make a good bond of the epoxy coating it was first of all necessary to impregnate the concrete with a fluid epoxy in order to ensure a perfect bond of the second thick epoxy layer. Furthermore, there is an advantage to have the second layer installed when the first one has not yet finished its polymerization.

When injection is performed, very good conditions are concerned since we use right away a fluid resin and as a consequence we are not only going to fill the cracks but also impregnate on both sides of these cracks the porous parts of the concrete allowing in this way an excellent bond.

Clearly, this is performed in one single phase. It is not advantageous to continue with a more viscous resin since the strength has nothing to do with fluidity.

When the crack is dirty, this clearly causes trouble. In general, dry cracks are preferred and occasionally wet cracks can be used but the contaminated cracks are worse than the wet cracks. When the crack is dirty, an attempt is made to wash it. This is not very easy. Especially when there is more or less carbonated limestone on the crack, it is necessary to dissolve it. This is clearly a handicap. However, quite happily the crack is not a perfect plane. It bends considerably. For this reason, it is possible to assume that, if a number of points are poorly adhesive, the solidity of the work will not be compromised.

Now, let us come to the epoxy-polyester dilemma. There are epoxies which hold perfectly in a moist environment. However, there are some which do not hold at all. Likewise, there are polyesters which adhere in a moist environment and others which do not adhere at all.

At the very least, good materials should be selected.

In a statistical study on commercial products, practically almost as many failures were found with polyesters as with epoxies. In both cases, certain additives make them competitive compatible with humidity and the adherence, in general, is better with extremely fluid products.

Indeed, a very fluid product will be able to easily penetrate into the crack and into the porous parts of the concrete at the same time forcing the water towards the interior of the concrete at a point where it is not dangerous.

Satisfied with losing somewhat in fluidity, we nevertheless use polyepoxies necessarily more viscous than certain polyesters when the crack exceeds several tenths of an mm in thickness.

What should not be done is to wish at any price to use an epoxy no matter what the fineness of the crack may be. We have found it necessary in a number of cases to intervene with colleagues who had wished to inject polyepoxies into cracks where clearly they could not penetrate.

Mr. de Schnakenbourg

Have you had experience with polyurethanes?

Mr. Caron

They absorb water to such an extent that it is difficult to use them as an adhesive. There would be a froth formation which would lessen adherence. We have studied the question with the various manufacturers.

Mr. Rocca

Can aqueous resins be produced from brackish water, sea water or brines, for example? Also, is there interaction between resins and hydrocarbons which could be in contact with the injected formations?

Mr. Caron

In order to reply to the first question, it is perfectly possible to use salt water. In some cases where it is desired to make the resin heavier, salt has been added to it and the results are good. The formula should be modified a little since the setting time is going to be changed. However, this question of dosage in the laboratory presents no problem.

Insofar as contact with hydrocarbons is concerned, according to our experience nothing happens. The aqueous resins are insoluble in oils and hydrocarbons in general. Most of the precondensed resins are likewise insoluble.

Mr. Louis

Have you made measurements of the expansion coefficient of all of these products? I am asking you this question because the cracks of concrete plugged with one of your products can then undergo quite small variations in dimension. This is understood either owing to mechanical effects or owing to effects of temperature change. Do the products used for filling have sufficient flexibility and elasticity?

Mr. Caron

With respect to concrete, there is a double advantage. On one hand, the strength is much greater (1000 bars in compression and 300 bars in traction). On the other hand, modulus of elasticity is much lower (10,000 to 20,000 bars whereas the modulus of the concrete is 300,000 bars). Consequently, we have the material which is much more deformable and much less sensitive to cracking than concrete.

However, in the "active" cracks, i.e., cracks which can move, this is still not enough. The resin should be made flexible by adding to it

elastomers in order to bring this modulus to 1000 bars for example only losing 10, 20 or 30% of the strength.

This is the completely conventional method which presents no problem.

Mr. Lebel

Have you an idea concerning elongation with rupture which you are able to obtain by these methods?

The question which I ask is, indirectly, the one concerning the capability for plugging on a durable basis, cracks of works made of reinforced concrete whose aperture can vary. In order to obtain satisfaction, it is clearly necessary for the injected product to cling to the lips of the cracks and have it undergo without damage the variations of their apertures.

Mr. Caron

This is somewhat the same question, but it is more precise and more difficult to answer.

On a test specimen with standardized traction, there will be elongations with rupture amounting to about 20% with an unmodified epoxy; 100% with an epoxy modified by polysulfides and perhaps 300% with a silicon. Everything is a function of the nature of the product. During this elongation, the test specimen will become narrower.

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The case of the crack is different. When the mass of concrete is going to be subjected to a traction stress, the resin in the crack will not be able to shrink. Since the Poisson coefficient of resins is in the vicinity of 0.5, there results from this that the modulus of elasticity in the crack is going to be much larger than the modulus previously measured.

A resin with a modulus of elasticity of 1000 bars with a test specimen will not behave in the crack quite as elastic as product.

I am not a very good theoretician and perhaps I have poorly explained this subject? ...

Mr. Lebel

Let us examine the case of a horizontal slab of reinforced concrete with dimensions 8.00 x 8.00 m and 0.08 m in thickness and lacking any coating or covering film. Let us assume that we have found different cracks on this slab, these cracks having apertures which do not exceed 1 mm in winter and which are practically invisible in summer. By injecting the cracks in winter, do you believe that a satisfactory result will be obtained?

Mr. Caron

Indeed, it is quite preferable to carry out the injection when the crack is at its maximum aperture, i.e., in winter. The adhesion will then work in compression.

This is, for example, what we have done at Tolla. This was more expensive since the volumes injected were greater, but it was the only way of being sure of having good work.

Mr. de Schnakenbourg

That was easier to do.

Mr. Caron

Yes, easier and more reliable.

Mr. Lebelle

If you inject in winter, will not the substance be expelled in summer?

Mr. Caron

That will make a small bulge whereas, in the other case, when going from 0.1 to 1 mm, there would be a separation.

Unidentified Voice

Or a crack on the side.

Mr. Caron

Yes, if the adhesion is too good.

Mr. Chairman

No more questions? ... It appears that Mr. Caron was quite correct in reserving a little time for the discussion, and I am very grateful to him for this. I thank him for his report and the discussion which followed.